HISTORY of LYSIMETER DESIGN and USE for EVAPOTRANSPIRATION MEASUREMENTS [1]

Terry A. Howell, Arland D. Schneider, and Marvin E. Jensen [2]
Member ASCE Member ASCE Fellow ASCE

Abstract

Lysimeters are devices for measuring percolation of water through soils and sampling soil water for chemical analyses. Lysimeters have been used for over 300 years to determine water use by vegetation. Precision lysimetry for measuring evapotranspiration (ET) has developed mainly within the past 50 years. Weighing lysimeter designs are quite varied to suite individual research requirements. Surface areas from 1.0 m^2 to over 29 m^2 have been used. ET accuracy depends directly on the lysimeter area, mass, and the type of scale, but many lysimeters have accuracies better than 0.05 mm. Few weighing lysimeters exceed 2.5-m profile depth. Mechanical, floating, hydraulic, and electronic scales have been used in weighing lysimeters with varying types of data recording methods. Lysimeter wall construction can affect heat transfer to the lysimeter and water flow along the walls. ET accuracy of weighing lysimeters can be affected by many additional factors (personnel traffic, cultural operations, crop height, etc.).

Introduction

Lysimeters have become standard tools in evapotranspiration (ET) and water quality research. An excellent review of the history of evaporation research and experimental methods is found in Brutsaert (1982). Historical accounts of ET research, in particular lysimeter developments, are found in Kohnke et al. (1940), Harrold and Dreibelbis (1951, 1958, and 1967), Tanner (1967), and Aboukhaled et al. (1982). Soileau and Hauck (1987) reviewed lysimetry research with an emphasis on percolate water quality, and Bergström (1990) discussed lysimetry applications for pesticide leaching research.

Lysimeter is defined in Webster's ***New Collegiate Dictionary*** as *a device for measuring the percolation of water through soils and for determining the*

---

[1] **Contribution from USDA-ARS, Southern Plains Area, Conservation & Production Research Laboratory, Bushland, Texas and Colorado Irrigation Management Institute, Colorado State University, Fort Collins, Colorado.**

[2] **Agricultural Engineers, USDA-ARS, P.O. Drawer 10, Bushland, TX 79012 and Director, Colorado Irrigation Management Institute, Colorado State University, CO 80523.**

soluble constituents removed in the drainage. The word *lysimeter* is derived from the Greek words *lysis* which means the dissolution or movement and *metron* which means to measure (Aboukhaled et al., 1982). Clearly, the word lysimeter means the measurement of the percolation of water in soil; although, other devices to remove water samples from soil are called "lysimeters". The lysimeter is foremost a device, generally a tank or container, to define the water movement across a soil boundary. The water use (evaporation, transpiration, or ET) can be determined by a balance of the water above this boundary. *Weighing lysimeters* determine ET directly by the mass balance of the water as contrasted to *non-weighing* lysimeters which indirectly determine ET by volume balance.

Kohnke et al. (1940) and Aboukhaled et al. (1982) attributed the first lysimeter for the study of water use to De la Hire of France in late 17th century. Salisbury and Ross (1969) described a lysimeter study conducted in the Netherlands in early 17th century (probably about 1620) by Van Helmont[3/]. Principle advances in ET lysimetry have centered on the measurement of the lysimeter mass and vacuum drainage and deeper lysimeters to more closely duplicate field conditions. The weighing mechanisms -- mechanical, floating, hydraulic, or electronic -- can be automated for electronic data recording. Major advances have occurred in the past 20 years in recording weighing lysimeter data.

Lysimeter designs have been copied or duplicated; however, Kohnke et al. (1940) cautioned *"that no one construction should be regarded as standard in a lysimeter and that a proper design can be made only by having an accurate knowledge of both the purpose of the experiment and of the pedologic, geologic, and climatic conditions."* Pruitt and Lourence (1985) cautioned each lysimeter user to critically evaluate all agronomic aspects to ensure the representative high quality ET data since major errors in ET data are possible even with an accurate lysimeter.

In ET research, lysimeters are simply containers or tanks filled with soil in which plants are grown. Kohnke et al. (1940) classified lysimeters according to type of soil block used, surface drainage, and methods of measuring soil water content. The method of drainage may be gravity or vacuum, or a water table may be maintained (Dugas et al., 1990). Lysimeters for ET research are usually classified as monolithic or reconstructed soil profiles, as weighing or non-weighing, and as gravity or vacuum drainage.

This paper will describe the evolution of design parameters commonly used for weighing lysimeters for ET measurements. Although non-weighing lysimeters are important and discussed in other papers in this proceedings, we have limited our discussions here to weighing lysimeters with *in situ* scales. Weighable lysimeters, which can be weighed periodically, are not discussed.

[3/] **Personal communication from Dr. C.H.M. van Bavel pointed out this reference.**

Lysimeter Design

ET Accuracy. ET measurement accuracy is dictated by the intended measurement period, i.e. for hourly, daily, or weekly time periods, etc., and few weighing lysimeters have ET accuracies better than 0.02 mm. The desired ET accuracy influecnes many weighing lysimeter design parameters, especially the type of scale. Three descriptions of lysimeter accuracy are often used and sometimes confused. *Resolution* is the last significant definable increment of the measurement; *precision* is the stated level of the measurement (variability among numerous measurements); and *accuracy* is the definable verification of the stated measurement compared to a "true" value (Fritschen and Gay, 1979).

Shape and Area. Lysimeter shape and area are based on the expected crops to be studied and their rooting depths. Many weighing lysimeters are rectangular in shape with a surface area that varies from 1.0 to over 29 m^2. When drainage flux measurements are important, the macro-porosity of the soil may dictate the area of the lysimeter necessary to provide a suitable soil sample (Ritchie et al., 1972). Circular lysimeters are inherently much stronger per unit container mass, but they pose questions about the "representativeness" of the lysimeter surface area in relation to row crop geometry. Differences between lysimeter and crop geometry can bias the soil water evaporation and crop transpiration relationship. Circular lysimeters should have a diameter several times the expected row width to minimize this bias. Lysimeter shape and area may not critically affect ET measurements for grass, alfalfa, or small grains or other broadcast planted crops. Width of a rectangular lysimeter should be an integer multiple of the row spacing. For an orchard or tree crop, the lysimeter area might be limited practically to only a single tree or vine (Green and Bruwer, 1979) in which case the plant to plant differences and soil variability must be carefully considered.

Depth. Lysimeter depth is a critical design parameter and will depend on the intended purpose of the lysimeter. For hydrological studies under periods of droughts and irrigation studies with significant soil water deficits, lysimeter depth should permit normal root development and soil water extraction. The deepest U.S. lysimeters range from 2.5 to 2.7 m (Harrold and Dreibelbis, 1958; Dugas et al., 1985). Van Bavel (1961) advised that lysimeter depth should permit the development of normal rooting density and rooting depth and provide similar "available" water profiles to the field profile. This applies whether or not a water table is maintained within the lysimeter. If shallow lysimeters (depth < 1.5 m) are used and representative field conditions are desired, then vacuum drainage must be used to establish or equalize the water potential at the lower boundary to that in the surrounding soil (Pruitt and Angus, 1960; Van Bavel, 1961; Tanner, 1967). Dugas et al. (1990) described a constant water table weighing lysimeter and separately measured the upward flow to a soybean crop.

Soil Profile Characteristics. Selection of lysimeter profile type -- monolithic or reconstructed -- often determines the representativeness of the ET data. Bergström (1990) provided an excellent discussion of monolithic versus reconstructed lysimeters. Exact soil physical, chemical, and/or vegetation characteristics can only be preserved by soil monoliths (Armijo et al., 1972; Fritschen et al., 1973; Reyenga et al., 1988; and Schneider et al., 1988). Naturally occurring differences (both vertically and horizontally) may affect soil monolith characteristics, particularly hydraulic conductivity (Ritchie et al., 1972). Schneider and Howell (1991) discuss monolith lysimeters and convenient methods for obtaining large soil monoliths. Kohnke et al. (1940) argued that future lysimeter designs should utilize soil monoliths. However, many weighing lysimeters have utilized reconstructed soil profiles for ET measurements, which have been verified with independent energy balance measurements as well as uniform visual crop appearance. Carefully reconstructed soil profiles have provided accurate ET data (Pruitt and Angus, 1960; Van Bavel and Myers, 1962) in many situations.

Weighing Mechanisms. Mechanical scales have been widely used in weighing lysimeters since the installation of the USDA Coshocton, OH lysimeters (Harrold and Dreibelbis, 1951). Many others have been constructed since then (Morris, 1959; Pruitt and Angus, 1960; McIlroy and Sumner 1961; Van Bavel and Myers, 1962; England and Lesesne, 1962; Libby and Nixon, 1963; McIlroy and Angus, 1963; Ritchie and Burnett, 1968; Mukammal et al., 1971; Armijo et al., 1972; Mottram and De Jager, 1973; Bhardwaj and Sastry, 1973; Von Hoyningen-Huene and Bramm, 1978; Hutson et al., 1980; Dugas et al., 1985; Marek et al., 1988; Reyenga et al., 1988). Mechanical scales permit large counter-weights to offset the container and soil mass to permit precise measurement of the mass change of the water within the lysimeter. Typical ET accuracy with mechanical lysimeter scales is 0.05 mm to 0.02 mm depending on counter-balancing and the lysimeter area and mass. Mechanical scales permit tracking of load cell drift, but also can be damaged by corrosion from condensation and rust at pivot points. Several weighing lysimeter installations have used air conditioning/heating/dehumidification equipment to prevent condensation on mechanical scales.

King et al. (1956) constructed a floating lysimeter using the principle of buoyancy. The lysimeter floated within a water-filled tank and the mass change was measured by the depth change of the fluid in a stilling well. McMillan and Paul (1961) used a $ZnCl_2$ solution (specific gravity of 1.9) instead of water to reduce the need for buoyancy chambers within the lysimeter, but $ZnCl_2$ solutions were found to have larger thermal expansion errors than water (Tanner, 1967). Aslyng and Kristensen (1961) used flotation to partially offset the *dead* mass of a lysimeter. Brooks et al. (1963) constructed a floating lysimeter at Davis, CA to measure ET (Lourence and Goddard, 1967) as well as surface drag (Goddard, 1970). ET accuracy of these floating lysimeters is 0.025 mm, which is often more accurate than mechanical scale weighing lysimeters.

Various types of hydraulic weighing lysimeters have been built since the 1950's (Ekern, 1958; Glover and Forsgaste, 1962; Swan, 1964; Hanks and Shawcroft, 1965; Black et al., 1968; Rose et al., 1966; Hillel et al., 1969; Fritschen et al., 1973; Dylla and Cox, 1973; Sammis, 1981). Hydraulic weighing lysimeters have inherent limitations due to the thermal stability of the measuring fluid. They typically have accuracies of 0.05 to 0.1 mm depending on the lysimeter area and mass, and are suitable to daily or less frequent ET measurements.

Strain-gage load cells have been used to measure the total mass of lysimeters (Frost, 1962; Green et al., 1974; Green and Bruwer, 1979; Sammis, 1981; McFarland et al., 1983; Kirkham et al., 1984; and Howell et al., 1985) as well as the final mass of mechanical scales (Van Bavel and Myers, 1962; Libby and Nixon, 1963; Ritchie and Burnett, 1968; Mukammal et al., 1971; Armijo et al., 1972; Hutson et al., 1980; Dugas et al., 1985; Marek et al., 1988). Load-cell scale lysimeters usually measure the total lysimeter mass without counter-weights, so the accuracy is dictated by the load-cell accuracy and data processing and recording instrumentation. Load cells seldom are more accurate than 0.01% (1 part in 10,000), so the final lysimeter accuracy is determined by the area to mass ratio of the lysimeter. A limitation of load cell scales is the temporal zero stability of the load cell (Sammis, 1981). Howell et al. (1985) periodically lifted a lysimeter above a scale using hydraulic jacks to check the load cell zero.

Construction. Many weighing lysimeters have used steel materials for the soil containers. Reinforced-fiberglass and plastic have been used for lysimeter containers to minimize heat conduction down the lysimeter walls (Pruitt and Angus, 1960). Black et al. (1968) found about 30 W/m^2 of energy consumed in heating steel lysimeter walls for two lysimeters in Wisconsin with bare soil conditions (the worst case) . Wall heating caused a lag between the lysimeter ET and field ET during the morning and the opposite effect during the afternoon. This error was about the same magnitude as the ET accuracy (30 W/m^2 is equivalent to about 0.04 mm/h of ET) and should be much less under vegetated conditions. Dugas and Bland (1991) found much greater apparent diurnal damping depths for soil temperature in small (0.25 m by 0.7 m by 1.7-m deep) and medium (0.5 m by 1.5 m by 1.7-m deep) lysimeters (0.21 m and 0.25 m, respectively) compared to a larger weighing lysimeter (Dugas et al., 1985) and the field soil (0.14 m and 0.12 m, respectively) for bare soil conditions and steel-walled lysimeters. Concrete has been used for lysimeter walls to minimize cost. Concrete walls must be much thicker than steel. Concrete walls should end about 0.3 m below the ground and thinner steel walls extended to the surface to avoid wall heating errors.

The gap between the outer and inner containers should be as narrow as practical to limit wall heating; however, sufficient clearance should be provided to avoid any wall contact. This gap has been as small as 8 mm (Van Bavel and Myers, 1962) to as large as 38 mm (Harrold and Dreibelbis, 1967). The total wall-gap width (outer wall thickness plus gap width plus lysimeter wall thickness) is greatly affected by the wall material. For instance, the Coshocton, OH lysimeters (Harrold and Dreibelbis, 1951) used thick concrete walls which had a total wall-gap width greater than 300 mm (about 25% of lysimeter area). These lysimeter walls were modified in 1962 (Harrold and Dreibelbis, 1964) to remove the grease seal, which interfered with the lysimeter mass determinations, and reduce the near-surface wall-gap width (Harrold and Dreibelbis, 1967). Total wall-gap area to lysimeter surface area has been as small as 1.5% in several lysimeter designs.

Various lysimeter wall construction designs have been used to prevent direct water flow along the walls. The Coshocton, OH lysimeters had 38-mm wide steel bars located inside the soil monoliths to prevent direct wall flow (Harrold and Dreibelbis, 1958). Brown et al. (1985) used a 50-mm wide tape barrier about 75-mm below the rim of their lysimeters to retard wall flow. The Bushland, TX lysimeters used 102-mm "drainage collars" placed 230 mm beneath the soil surface (Marek et al., 1985) to minimize direct wall water flow in the expansive Pullman clay loam soil. The Bushland weighing lysimeters like the Coshocton lysimeters segmented the lysimeter bottom. Although drainage through the Pullman clay loam profile at Bushland is a small part of the water balance, considerably greater drainage flux has been observed from the wall sections (50% of lysimeter area) compared to the inner section (remaining 50% of lysimeter area) indicating some wall flow.

Siting. Lysimeters are intended to represent soil and plant conditions in fields or natural environments. They should be located away from taller obstructions that may alter incident radiation and wind patterns, and the topography should be as level as practical. The site should have uniform soil conditions to permit uniform crop development. Hill-top locations may have non-representative wind regimes. The lysimeter buffer area must be large enough to provide a typical micro-environment. A larger buffer area (or fetch of the same vegetation) is required in arid settings than in humid settings. Many investigators recommend an upwind fetch distance greater than 50 m and site area of 1 ha. An example of the effect of inadequate fetch was reported by Dugas and Bland (1989) in which ET was 44% greater in relation to total net radiation and soil heat flux for a 0.01 ha soybean plot surrounding a 3-m^2 weighing lysimeter at Temple, TX when the surrounding fallow soil was dry compared to similar conditions with a wet surrounding soil.

Lysimeter Operation

Cultural Operations. Cultural operations (fertilizing, tilling, planting, harvesting, etc.) are normally preformed on the lysimeter and the immediate surrounding area by hand to simulate field practices and to assure that crop development is similar to that in the surrounding field. Common problems involve service personnel and visitor traffic to the site. Trails in the crop can change the hydrology of the site and crop development surrounding the lysimeter. Many investigators use walkways (boards, light steel, bricks, etc.) to permit personnel traffic to the lysimeter site when the soil surface is wet.

Representativeness of lysimeter vegetation greatly affects ET. Pruitt and Lourence (1985) showed examples where even small differences between the lysimeter and surrounding crop greatly affected the ET. Meyers et al. (1990) reported a 30% ET reduction for soybean in a lysimeter with 0.1-m shorter crop. The ET reduction was removed when 0.1 ha of the surrounding

crop around the lysimeter was shortened by 0.15 m (Meyer and Mateos, 1990). Van Bavel et al. (1963) demonstrated the dramatic effect of an intentional crop height discontinuity on ET measured with a weighing lysimeter.

Data Recording. Lysimeter data recording methods have changed dramatically over the past 20 years with developments of portable, d.c.-powered data acquisition systems using micro-computers. The Coshocton, OH lysimeters (Harrold and Dreibelbis, 1958) were the first weighing lysimeters to continuously record lysimeter mass. The Phoenix, AZ lysimeters (van Bavel and Myers, 1962) were the first to utilize automated data recording. Many weighing lysimeters still use hand recording techniques, but computerized data acquisition systems can process lysimeter and meteorological data and perform control functions (drainage, etc.) (Howell et al., 1985). The integration period for lysimeter mass has varied considerably from a few minutes to an hour depending on data recording methods. Since wind interferences limit weighing lysimeter accuracy to about 0.02 mm or greater, lysimeter mass measurements more frequent than 15 min. to 30 min. are seldom required.

Conclusions

Lysimeters have been used for centuries, but measurement and instrumentation technologies have been improved greatly during the past 50 years. Large potential errors can be reduced by designing lysimeters to meet specific requirements, by proper lysimeter operation, and by managing the lysimeter site according to design requirements. Many problems can be avoided by reviewing lysimeter literature before designing new lysimeters.

References

Aboukhaled, A., A. Alfaro, and M. Smith. 1982. Lysimeters. Food and Agr. Org. of the United Nations, FAO Irrig. and Drain. Paper No. 39. 68 p.

Armijo, J.D., G.A. Twitchell, R.D. Burman, and J.R. Nunn. 1972. A large, undisturbed, weighing lysimeter for grassland studies. Trans. ASAE 15:827-830.

Aslyng, H.C. and K.J. Kristensen. 1961. Water balance recorder. Irrig. Drain. Div., Am. Soc. Civil Engr. 87:15-21.

Bergström, L. 1990. Use of lysimeters to estimate leaching of pesticides in agricultural soils. Environ. Poll. 67:325-347.

Bhardwaj, S.P. and G. Sastry. Development and installation of a simple mechanical weighing lysimeter. Trans. ASAE 22:797-802.

Black, T.A., G.W. Thurtell, and C.B. Tanner. 1968. Hydraulic load cell lysimeter, construction, calibration and tests. Soil Sci. Soc. Am. Proc. 32:623-629.

Brooks, F.A., W.O. Pruitt, and D.R. Nielsen. 1963. Investigation of energy and mass transfers near the ground including the influences of the soil-plant-atmosphere system. Final Report, Contract No. DA-36-039-SC-80334, USAEPG, Fort Huachuca, AZ, University of California, Davis. 285 p.

Brown, K.W., J.C. Thomas, and M.W. Aurelius. 1985. Collecting and testing barrel sized undisturbed soil monoliths. Soil Sci. Soc. Am. J. 49:1067-1069.

Brutsaert, W. 1982. Evaporation into the atmosphere. D. Reidel Publ. Co., Dordrecht, The Netherlands. 299 p.

Dugas, W.A. and W.L. Bland. 1989. Effect of bordering soil surface moisture conditions on evaporation from soybean. Field Crops Res. 21:161-166.

Dugas, W.A. and W.L. Bland. 1991. Springtime soil temperatures in lysimeters in Central

Texas. Soil Sci. (in press)

Dugas, W.A., W.S. Meyer, H.D. Barrs, and R.J. Fleetwood. 1990. Effects of soil type on soybean crop water use in weighing lysimeters. II. root growth, soil water extraction and water-table conditions. Irrig. Sci. 11:77-81.

Dugas, W.A., D.R. Upchurch, and J.T. Ritchie. 1985. A weighing lysimeter for evapotranspiration and root measurements. Agron. J. 77:821-825.

Dylla, A.S. and L.M. Cox. 1973. An economical hydraulic weighing evapotranspiration tank. Trans. ASAE 16:294-295, 301.

Ekern, P.E. 1958. Dew measurements at PRI field station (Wahiawa). Pineapple Res. Inst. News 6:134-135.

England, C.B. and E.H. Lesesne. 1962. Evapotranspiration research in Western North Carolina. Agric. Engr. 43:526-528.

Fritschen, L.J., L. Cox, and R. Kinerson. 1973. A 28-m Douglas-fir in a weighing lysimeter. Forest Sci. 19:256-261.

Fritschen, L.J. and L.W. Gay. 1979. Environmental instrumentation. Springer-Verlag, New York, NY. 216 p.

Frost, K.R. 1962. A weighing evapotranspirometer. Agric. Engr. 43:160.

Glover, J. and J.A. Forsgate. 1962. Measurement of evapotranspiration from large tanks of soil. Nature 195:1330.

Goddard, W.B. 1970. A floating drag-plate lysimeter for atmospheric boundary layer research. J. Appl. Meteorol. 9:373-378.

Green, G.C. and W. Bruwer. 1979. An improved weighing lysimeter facility for citrus tree evapotranspiration studies. Water SA 5:189-195.

Green, G.C., W.P. Burger, and J. Conradie. 1974. Lysimetric determination of citrus tree evapotranspiration. Agrochemophysica 6:35-42.

Hanks, R.J. and R.W. Shawcroft. 1965. An economical lysimeter for evapotranspiration studies. Agron. J. 57:634-636.

Harrold, L.L. and F.R. Dreibelbis. 1951. Agricultural hydrology as evaluated by monolith lysimeters. Tech. Bull. No. 1050, U.S. Dept. of Agric., Washington, D.C. 149 p.

Harrold, L.L. and F.R. Dreibelbis. 1964. Evidence of errors in evaluation of dew amounts by the Coshocton lysimeters. Intl. Assoc. Sci. Hydrol. 65:425-431.

Harrold, L.L. and F.R. Dreibelbis. 1958. Evaluation of agricultural hydrology by monolith lysimeters. Tech. Bull. No. 1179, U.S. Dept. of Agric., Washington, D.C. 166 p.

Harrold, L.L. and F.R. Dreibelbis. 1967. Evaluation of agricultural hydrology by monolith lysimeters. Tech. Bull. No. 1367, U.S. Dept. of Agric., Washington, D.C. 123 p.

Hillel, D., S. Gairon, V. Falkenflug, and E. Rawitz. 1969. New design of low-cost hydraulic lysimeter system for field measurement of evapotranspiration. Israel J. Agric. Res. 19:57-63.

Howell, T.A., R.L. McCormick, and C.J. Phene. 1985. Design and installation of large weighing lysimeters. Trans. ASAE 28:106-112, 117.

Hutson, J.L., G.C. Green, and W.S. Meyer. 1980. A weighing lysimeter facility at Roodeplaat for crop evapotranspiration studies. Water SA 6:41-46.

King, K.M., C.B. Tanner, and V.E. Suomi. 1956. A floating lysimeter and its evaporation recorder. Trans., Am. Geophys. Union 37:738-742.

Kirkham, R.R., G.W. Gee, and T.L. Jones. 1984. Weighing lysimeters for long-term water balance investigations at remote sites. Soil Sci. Soc. Am. J. 48:1203-1205.

Kohnke, H., F.R. Dreibelbis, and J.M. Davidson. 1940. A survey and discussion of lysimeters and a bibliography on their construction and performance. Misc. Publ. No. 372, U.S. Dept. of Agric., Washington, D.C. 68 p.

Libby, F.J. and P.R. Nixon. 1963. A portable lysimeter adaptable to a wide range of site situations. Intl. Assoc. Sci. Hydrol. 62:153-158.

Lourence, F.J. and W.B. Goddard. 1967. A water-level measuring system for determining evapotranspiration rates from a floating lysimeter. J. Appl. Meteorl. 6:489-492.

Marek, T.H., A.D. Schneider, T.A. Howell, and L.L. Ebeling. 1988. Design and construction of large weighing monolithic lysimeters. Trans. ASAE 31:477-484.

McFarland, M.J., J.W. Worthington, and J.S. Newman. 1983. Installation of a large twin weighing lysimeter facility. Trans. ASAE 26:1717-1721.

McIlroy, I.C. and D.E. Angus. 1963. The Aspendale multiple weighed lysimeter installation. Div. Meteorol. Phys. Paper No. 14, CSIRO, Australia. 27 p.

McIlroy, I.C. and C.J. Sumner. 1961. A sensitive high-capacity balance for continuous automatic weighing in the field. J. Agric. Engr. Res. 6:252-258.

McMillan, W.D. and H.A. Paul. 1961. Floating lysimeter. Agric. Engr. 42:498-499.

Meyer, W.S., W.A. Dugas, H.D. Barrs, R.C.G. Smith, and R.J. Fleetwood. 1990. Effects of soil type on soybean crop water use in weighing lysimeters. I. evaporation. Irrig. Sci. 11:69-75.

Meyer, W.S. and L. Mateos. 1990. Effects of soil type on soybean crop water use in weighing lysimeters. I. effect of lysimeter canopy height discontinuity on evaporation. Irrig. Sci. 11:233-237.

Morris, L.G. 1959. A recording weighing machine for the measurement of evapotranspiration and dewfall. J. Agric. Engr. Res. 4:161-173.

Mottram, R. and J.M. De Jager. 1973. A sensitive recording lysimeter. Agrochemophysica 5:9-14.

Mukammal, E.I., G.A. McKay, and V.R. Turner. 1971. Mechanical balance-electrical readout weighing lysimeter. Boundary-Layer Meteorol. 2:207-217.

Pruitt, W.O. and D.E. Angus. 1960. Large weighing lysimeter for measuring evapotranspiration. Trans. ASAE 3:13-15, 18.

Pruitt, W.O. and F.J. Lourence. 1985. Experiences in lysimetry for ET and surface drag measurements. pp. 51-69. *In: Advances in Evapotranspiration* , Am. Soc. of Agric. Engr., St. Joseph, MI.

Reyenga, W., F.X. Dunin, B.C. Bautovich, C.R. Rath, and L.B. Hulse. 1988. A weighing lysimeter in a regenerating eucalypt forest: design, construction, and performance. Hydrol. Processes 2:301-314.

Ritchie, J.T. and E. Burnett. 1968. A precision weighing lysimeter for row crop water use studies. Agron. J. 60:545-549.

Ritchie, J.T., D.E. Kissel, and E. Burnett. 1972. Water movement in undisturbed swelling clay soil. Soil Sci. Soc. Am. Proc. 36:874-879.

Rose, C.W., G.F. Byrne, and J.E. Begg. 1966. An accurate hydraulic lysimeter with remote weight recording. Div. Land Res. Tech. Paper No. 27, CSIRO, Australia. 31 p.

Salisbury, F.B. and C. Ross. 1969. Plant physiology. Wadsworth Publ. Co., Inc., Belmont, CA. 764 p.

Sammis, T. 1981. Lysimeter for measuring arid-zone evapotranspiration. J. Hydrol. 49:385-394.

Schneider, A.D., T.A. Howell, and J.L. Steiner. 1989. An evapotranspiration research facility using monolithic lysimeters from three soils. ASAE Paper No. 89-2089. Am. Soc. of Agric. Engr., St. Joseph, MI. 13 p.

Schneider, A.D. and T.A. Howell. 1991. Large weighing monolith lysimeters: calibration and use. *In:* Proceedings of the ASCE Lysimetry Symposium (this proceedings).

Schneider, A.D., T.H. Marek, L.L. Ebeling, T.A. Howell, and J.L. Steiner. 1988. Hydraulic pulldown procedure for collecting large soil monoliths. Trans. ASAE 31:1092-1097.

Soileau, J.M. and R.D. Hauck. 1987. A historical review of U.S. lysimetry with emphasis on fertilizer percolation losses. Int. Conf. on Infiltration Development and Application, Honolulu, HI. 25 p.

Swan, J.B. 1964. Evapotranspiration from irrigated snap-beans and potatoes. Ph.D. Dissertation, Univ. of Wisconsin, Madison. 78 p.

Tanner, C.B. 1967. Measurement of evapotranspiration. pp. 534-574. *In:* R.M. Hagan, H.R. Haise, and T.W. Edminster (eds.) *Irrigation of Agricultural Lands*, Agron. Monograph No. 11, Am. Soc. Agron., Madison, WI.

Van Bavel, C.H.M. 1961. Lysimetric measurements of evapotranspiration in the Eastern United States. Soil Sci. Soc. Am. Proc. 25:138-141.

Van Bavel, C.H.M., L.J. Fritschen, and W.E. Reeves. 1963. Transpiration of sudangrass as an externally controlled process. Science 141:269-270.

Van Bavel, C.H.M. and L.E. Myers. 1962. An automatic weighing lysimeter. Agric. Engr. 43:580-583, 586-588.

Von Hoyningen-Huene, J. and A. Bramm. 1978. Die wagbare unterdrucklysimeteranlage in Braunschweig-Völkenrode-aufbau und erste Erfahrungen. Landbauforschung Völkenrode 28:95-102.

History of Lysimeter Design and Effects of Environmental Disturbances

Philippe Grebet[1] and Richard H. Cuenca

Member ASCE

Abstract

A brief history of developments in lysimeter design is indicated. Disturbances introduced by the measurement system on the surrounding environment are discussed. The use of weighing lysimeters for accurate evapotranspiration measurement is considered. Points covered in the discussion are also applicable to other types of lysimeters.

Environmental disturbances generated by alteration of the soil structure inside as well as outside the lysimeter arise from:

a) Removal of a substantial volume of soil and compression of the soil surrounding the lysimeter.

b) Insulation of a soil block from its surroundings causing fissures between the soil and the lysimeter side walls, the effect of the soil-air boundary at the bottom of the lysimeter, and the suppression of the horizontal subterranean flow of water.

c) Architecture of the weighing system which requires a large volume for the system and in some cases a service tunnel beneath the soil tank.

d) Management of the lysimeter which should be exactly the same as that of the surrounding field, but often is not.

Introduction

This paper is based on the interesting work of Kohnke et al. (1940) and on the authors' experience in the design, installation and operation of many lysimeters in different parts of the world. Lysimeters have been employed for approximately three centuries to study the relations between soil, water and plants. Table 1 summarizes some key developments in lysimeter design and construction.

1 Research Engineer, Laboratoire de Bioclimatologie, I.N.R.A. 78850 Thiverval-Grignon, France and Associate Professor, Department of Bioresource Engineering, Oregon State University, Corvallis, OR 97331-3906

Table 1. Main developments in lysimeter system design.

Lysimeter Milestone	Investigator	Location	Year
First lysimeter	de la Hire	Paris France	1688
First lysimeter with run-off provision	Dalton	Manchester United Kingdom	1796
First soil-block lysimeter	Lawes and Gilbert	Rothamsted United Kingdom	1870
First large comparative lysimeter study	Wollny	Munich Germany	1880
First Ebermeyer lysimeter	Welbel	Ploti USSR	1903
First weighing lysimeter	Seelhorst	Göttingen Germany	1906
First soil-block weighing lysimeter	Weaver and Crist	Lincoln, NE USA	1923
First soil-block weighing lysimeter with self-recording mechanism	Harrold and Dreibelbis	Coshocton, OH USA	1936
First lysimeter with tensiometers	Iowa State College Soil Cons. Service	Clarinda, IA USA	1937

Initially the purpose of lysimeter studies was related principally to hydrology, particularly the quantification of soil water percolation. Later studies were directed at the chemical composition of the percolate as well as the quantity. Thornthwaite was presumably the first to apply lysimeters for the measurement of evapotranspiration (ET) in field conditions (Thornthwaite et al., 1946).

The lysimeter is a container which is set into the soil to separate a particular soil volume which is observed and analyzed. It is in fact an instrument installed in a solid medium to measure the dynamic phenomenon of water movement. Difficulties which affect the accuracy of this measurement arise from the installation and from the geometry of the measurement system.

Installation

Filling the Lysimeter. Installation consists of removing a volume of soil, setting the components of the lysimeter into the volume vacated, and replacing the soil inside and outside the lysimeter so as to reconstitute the soil close to its natural state. Three methods of reconstitution of the soil can be distinguished (Kohnke et al., 1940): a) Ebermeyer, b) filled-in, and c) monolith, or undisturbed soil-block.

a) **Ebermeyer method:** The soil is left *in situ* with no side walls separating a definitive soil block from the adjacent soil. A percolate collecting funnel is placed under the soil to be monitored and a tube attached to the funnel conveys the percolate into a receptacle. This type cannot be employed for evapotranspiration measurements.

b) **Filled-in method:** This type consists of a container with vertical walls, an open top, and a bottom that provides for percolation. The container is filled with the soil which was removed from its original location. Sometimes the soil is screened and mixed to make it uniform.

c) **Undisturbed soil-block method:** This container also has vertical walls, an open top, and a bottom that provides for percolation. A monolithic block of soil is encased in the prepared lysimeter which insulates it from the surrounding soil.

The filled-in method is the most commonly used because of the relative ease and cost. Using this method, the soil structure undergoes change during its removal from the original site and the process of mixing and replacing it in the lysimeter container. Close to the soil surface, within the plow layer, this is generally not objectionable because this is the part of the field normally disturbed by agricultural implements. The mixing of the complete soil profile, however, can have a significant effect on soil water properties, in particular bulk density, and soil structure and therefore on soil water movement. To help obviate this problem, many researchers refill the lysimeter using a number of soil horizons of the same thickness and soil type as found in the natural state at the lysimeter site (Howell et al., 1985). This aids in maintaining a similar overall drainage pattern in the lysimeter as in the natural field, but does not reduce the problem of changes in micropore size and orientation and changes in bulk density.

The potential effects of changes in soil water properties during the refilling process can be observed in Figure 1. The figure indicates three growing seasons of lysimeter-measured ET versus that estimated by a form of the Penman method from a lysimeter operated at Pergamino in Argentina. The lysimeter used was a drainage type. The first season of operation after refilling was 1970-71. During this year there was the greatest difference between measured and estimated cumulative ET. The measured ET is considerably larger than that estimated by a meteorological method and plant growth in the lysimeter was observed to be more vigorous than in the adjacent field. In 1972-73 the difference between the two methods is much less noticeable with an even slightly less difference in 1972-73. By the second or third year of operation, there is a consistency between the two measurement methods indicating that the soil water properties have stabilized. These results are typical to those observed in other new lysimeter installations (Howell et al., 1985).

The monolith or undisturbed soil-block method is the most cumbersome of lysimeter installation methods and generally the most expensive (Bhardwaj and Sastry, 1979; Marek et al., 1988). The construction required for insulation of the monolith or undisturbed soil-block generates large excavations which have the potential of modifying the soil surrounding the lysimeter in two ways:

a) If the monolith is replaced at the same location where it was extracted, the physical characteristics of the surrounding soil will be modified not only by removal but also by compression due to the machinery employed during construction.

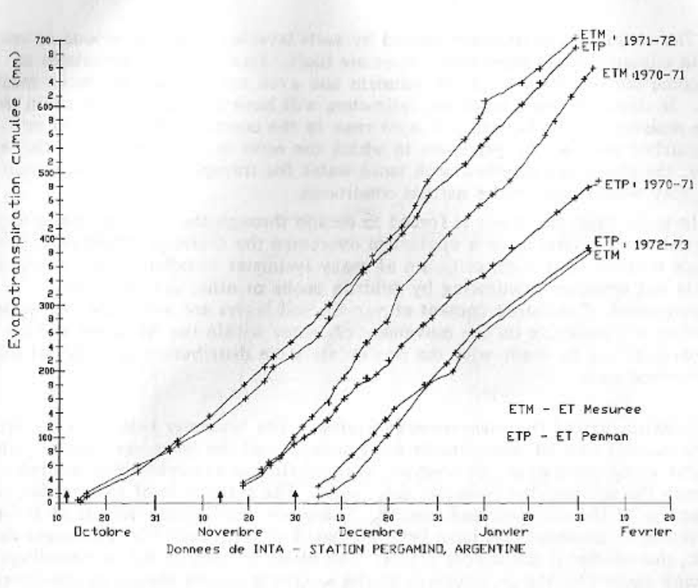

Figure 1: Comparison of cumulative ET of a corn crop and Penman estimated ET at the INTA research station in Pergamino (Argentina).

b) If the monolith is placed at some location different from where it was extracted, the physical characteristics of the surrounding soil will be different from that where it was extracted and therefore different from that inside the lysimeter.

Insulation of the Soil Block. The greatest error in many types of lysimeters occurs at the boundary of the lysimeter soil and the air beneath it. Gravitational water draining to this point has to overcome the surface tension at the interface before it can drain completely from the lysimeter. Many early lysimeters, including drainage types, were installed without taking into account this drainage-impeding effect of the soil-air boundary at the bottom of the lysimeter.

Frequently sand and/or gravel are placed at the bottom of the lysimeter to act as a stable buffer between the lysimeter soil mass and the drain pipe. This practice was also followed to promote better drainage of the gravitational water in the lysimeter. An investigation by Kohnke et al. (1940) showed that at the end of the dry season there was an accumulation of soil moisture above the soil-sand boundary as well as above each boundary between soil layers of different texture. A particularly large accumulation of water was observed in the lower part of a sand horizon just above a screen at the lysimeter bottom.

The restriction to drainage caused by such layering is not so serious in very humid climates where percolation rates are high. Enough water percolates to overcome the surface-tension impediment and even natural soils are moist most of the time. In drier climates, however, lysimeters will have a tendency to contain much more moisture in the bottom soil layer than in the corresponding layer in an undisturbed profile. In lysimeters in which the roots of the plants reach this excess water, the plants are supplied with more water for transpiration and more nutrients than they would have under natural conditions.

In some cases the water is forced to escape through the open bottom after a sufficient hydrostatic head is applied to overcome the drainage impeding effect of surface tension. A typical criticism of many lysimeter installations not equipped with profile soil moisture monitoring by neutron probe or other device is that measurements of moisture content of various soil layers are not made. Information is therefore not available on the movement of water within the lysimeter and no comparisons can be made with the profile moisture distribution of adjacent soils in an undisturbed state.

Architecture of the Measurement System. The lysimeter side walls do not permit the horizontal flow of water inside the lysimeter and the lysimeter bottom restricts vertical water movement. In contrast, vertical flow is exacerbated at the interface between the soil and the lysimeter side walls. The magnitude of this border effect is a function of the soil type and texture. These are unavoidable defects of lysimeters and potential consequences have been indicated above. Basically, the larger the soil block, the smaller is the border effect. The modifications of the surroundings outside the tank caused by the architecture of the weighing system should be considered. These modifications disturb the flow of water as well as the heat flux close to the lysimeter by the discontinuity created in the soil for housing the weighing system and the instrument tunnel.

Grebet (1982) presented a survey of weighing lysimeters installed since 1940 with emphasis on the discontinuity introduced by the measurement instrumentation in the medium where the measurements have to be made. He related the relative effects to the accuracy of the weighing system employed. These effects are not generally visible on the surface of the field. A lysimeter with a well-established crop in good condition and well maintained in the middle of the field may hide from view a large-volume "under structure" at the 15 cm depth below the soil surface. Figure 2, taken from Grebet (1982), illustrates this point. The lysimeters shown in the figure are drawn to the same scale. They include a) floating lysimeter (on water) of Popov (1959), b) mechanical balance of Eldin (1968), c) mechanical-electronic system of Ritchie and Burnett (1968), and d) electronic system of Grebet (1965). In this figure, S = surface border effect, V = volume border effect, and P = precision indicated by the original investigator where,

$$S = \left[\frac{\text{soil tank surface area}}{\text{total structure surface area}} \right] \times 100$$

$$V = \left[\frac{\text{soil tank volume}}{\text{total structure volume}} \right] \times 100$$

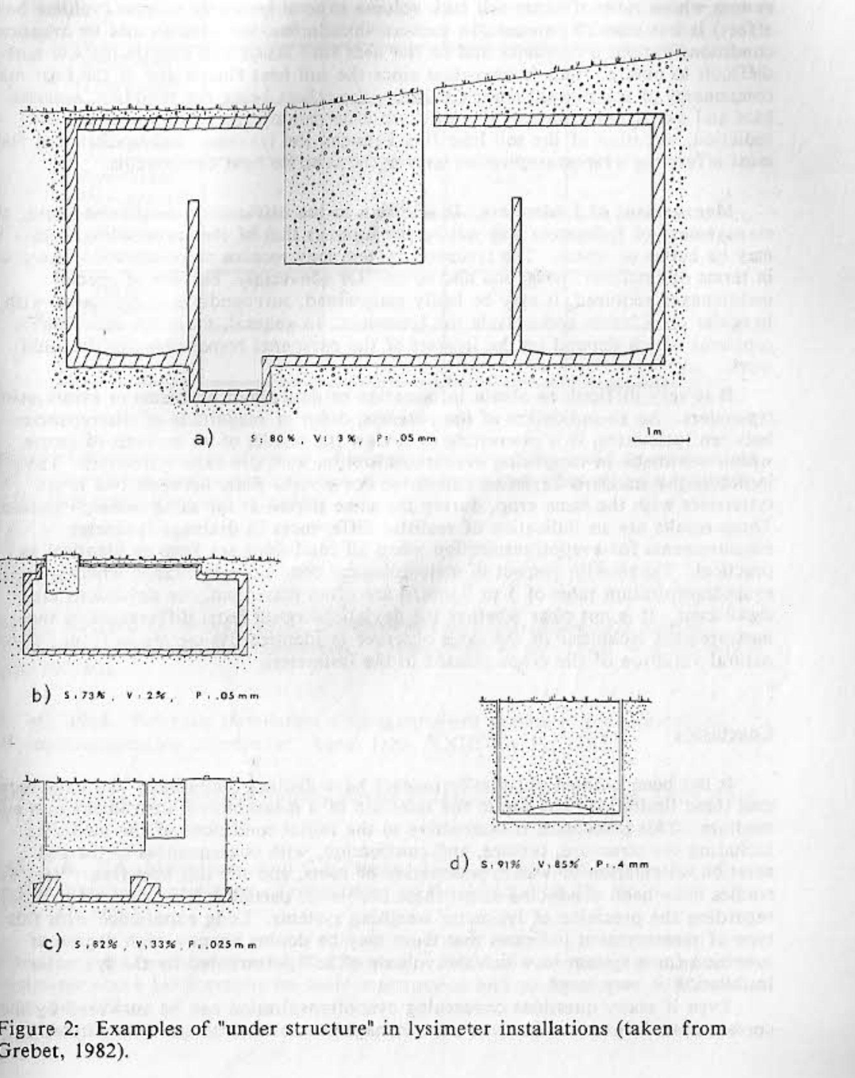

Figure 2: Examples of "under structure" in lysimeter installations (taken from Grebet, 1982).

There may be doubts about the validity of evapotranspiration measurements when the energy balance of the tank of soil is only representative of a limited field and the depth of the surrounding soil is reduced to that of the plow layer. It may be asked what is the meaning of a stated precision of better than 0.1 mm with a weighing system whose ratio of inner soil tank volume to total lysimeter volume (volume border effect) is less than 20 percent. In such an installation, information and on evaporative conditions around a lysimeter and on the heat flux inside and outside the soil tank is difficult to obtain. This is important since the soil heat flux is one of the four major components of the diurnal energy balance, the others being net radiation, sensible heat and evapotranspiration. If a uniform crop canopy results in a uniform net radiation, variation of the soil heat flux between the lysimeter and undisturbed field must affect the evapotranspiration and/or the sensible heat components.

Management of Lysimeters. In addition to the difficulties mentioned above, the management of lysimeters may not be the same as that of the surrounding field - it may be better or worse. The lysimeter system may receive more attention, more care in terms of fertilizer, irrigation and so on. Or conversely, because of special maintenance required, it may be badly maintained, surroundings compressed, with an irregular crop inside and outside the lysimeter. In general, these are unavoidable problems which depend on the interest of the personnel responsible for the field work.

It is very difficult to obtain information or data about problems or errors using lysimeters. As an indication of the potential order of magnitude of discrepancies between lysimeters, it is interesting to review the results of an analysis of errors which was made in measuring evapotranspiration with drainage lysimeters. Table 2 indicates the standard deviation calculated for several years between two to six lysimeters with the same crop, during the same period at the same research station. These results are an indication of realistic differences in drainage lysimeter measurements for evapotranspiration when all conditions are keep as identical as practical. Taken with respect to meteorological conditions in France where evapotranspiration rates of 5 to 6 mm/d are often maximum, the deviations are significant. It is not clear whether the deviations result from differences in the measurement technique of the same observer in identical lysimeters or from potential natural variation of the crops planted to the lysimeters.

Conclusion

It has been pointed out that lysimeters have distinct limitations. We have seen that these limitations are due to the insertion of a measurement instrument into a solid medium. This placement is destructive to the initial conditions of the medium, including the structure, texture, and compaction, with consequences to the soil aeration, circulation of water, penetration of roots, and the soil heat flux. Very few studies have been conducted about these problems, particularly in contrast to studies regarding the precision of lysimeter weighing systems. Long experience with this type of measurement indicates that there may be doubts about a high degree of precision for a system in which the volume of soil perturbated by the lysimeter installation is very large.

Even if many questions concerning evapotranspiration can be answered by the correct use of these instruments, poor management or maintenance constitutes a potentially important source of errors. Lysimeter investigations could be made more useful by describing more completely not only the installations but also the methods used for data acquisition and recording.

Table 2. Standard deviation of ET measurements in mm of water for drainage lysimeters at different locations for various crops over a time period of 7 days except in Toulouse where the period is 10 days.

Crop (*Culture*)	Clermont Ferrand	Dijon	Rennes	Toulouse
Sunflower (*Tournesol*)				8.2
Sorghum (*Sorgho*)				4.0
Rye Grass (*Ray-grass*)			2.6	
Fescue (*Fétuque*)	5.8	5.9	6.8	5.0
Alfalfa (*Luzerne*)	7.9		9.7	7.8
Soybean (*Soja*)				4.3

References

Bhardwaj, S.P. and G. Sastry. 1979. Development and Installation of a Simple Mechanical Weighing Type Lysimeter. *Transactions of the ASAE*, Vol. 22, No. 4, pp. 797-802.

Eldin, M. 1968. Nouvelle installation d'enregistrement precise et economique de l'evapotranspiration potentielle. Agro. Trop. XXIII No. 11, 1182.

Grebet, Ph. 1982. Evapotranspiration, mesure et calcul. These Doc. Ing. Univ. Paris VI, 1982.

Howell, T.A., R.L. McCormick and C.J. Phene. 1985. Design and Installation of Large Weighing Lysimeters. *Transactions of the ASAE*, Vol. 28, No. 1, pp. 106-112, and 117.

Kohnke, H., F.R. Dreibelbis, and J.M. Davidson. 1940. A survey and discussion of lysimeter and a bibliography on their construction and performance. USDA Misc. Pub. No. 372.

Marek, T.H., A.D. Schneider, T.A. Howell and L.L Ebeling. 1988. Design and Construction of Large Weighing Monolithic Lysimeters. *Transactions of the ASAE*, Vol. 31, No. 2, pp. 477-484.

Popov, O.V. 1959. Lysimeters and hydraulic soil evaporimeters. AIHS Hannoversch-Munden, No. 49, T 2, Vol. 12, pp. 26-37.

Ritchie, J. T., and E. Burnett. 1968. A precision weighing lysimeter for row crop water use studies. Agronomy Journal, No. 60, pp. 545-549.

Thorthwaite, C.W., H.G. Wilm et al. 1946. Report of the Committee on Evaporation and Transpiration. Transactions of the American Geological Institute, Vol. 27, No. 5, pp. 721-723.

DEVELOPMENT OF HANFORD SITE LYSIMETER FACILITIES

S.J. Phillips, J.F. Relyea, C.J. Kemp, N.R. Wing[1]; M.D. Campbell, G.W. Gee, M.J. Graham, R.R. Kirkham[2]; M.S. Ruben[3]

Abstract

Lysimeters have been constructed at the Hanford Site near Richland, Washington to quantify mechanisms that affect migration of radioactive and hazardous waste in geologic media. The history of design and construction of specific lysimeter facilities is summarized. Design criteria and construction specifications are also provided for comparison of facilities.

Introduction

Numerous lysimeter facilities have been designed and constructed at the Hanford Site since 1972. The general purpose of these facilities is to measure factors affecting transport of radioactive and hazardous waste constituents in unsaturated geologic media under field conditions. Quantitative assessment, simulation, and prediction of transport gained from lysimeter data thus can be used to augment selection of waste site remediation alternatives (Runchal and Sagar, 1989).

The experience gained by design, construction, and operation of each lysimeter facility provides a sound basis for successive facilities. Innovative construction equipment, methodologies, and materials fabrication practices developed in support of lysimetry have significantly improved facilities operations.

The following provides a brief summary of five lysimeter facilities that represent a divergence in design and construction practices yet demonstrate unanimity in purpose. The overview of these facilities demonstrates the history and development of lysimeters at the Hanford Site in support of defense and environmental restoration missions. Other papers presented at this symposium will give specific operational detail and results of Hanford lysimeter activities.

[1]Westinghouse Hanford Company, P.O. Box 1970, Richland, WA 99352
[2]Pacific Northwest Laboratory, P.O. Box 999, Richland, WA 99352
[3]Kaiser Engineers Hanford Company, P.O. Box 888, Richland, WA 99352